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On the Variability of Tool Wear and Life at Disparate Operating Parameters

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Abstract**—**The stochastic nature of tool life using conventional discrete-wear data from experimental tests usually exists due to many individual and interacting parameters. It is a common practice in batch production to continually use the same tool to machine different parts, using disparate machining parameters. In such an environment, the optimal points at which tools have to be changed, while achieving minimum production cost and maximum production rate within the surface roughness specifications, have not been adequately studied.

In the current study, two relevant aspects are investigated using coated and uncoated inserts in turning operations: (i) the accuracy of using machinability information, from fixed parameters testing procedures, when variable parameters situations are emerged, and (ii) the credibility of tool life machinability data from prior discrete testing procedures in a non-stop machining.

A novel technique is proposed and verified to normalize the conventional fixed parameters machinability data to suit the cases when parameters have to be changed for the same tool. Also, an experimental investigation has been established to evaluate the error in the tool life assessment when machinability from discrete testing procedures is employed in uninterrupted practical machining**.**

Keywords**—**Machinability; tool life; tool wear; wear variability.

I. Introduction

IT is a common practice both in conventional and modern machining operations that the same insert is used for a succession of cuts using different conditions throughout its useful lifetime. This is a common strategy in modern manufacturing systems such as Adaptive Control *AC* where the cutting parameters are subject to continual automatic change when the need arises so as to suit a prespecified objective function. The major problem in such changing parameters situations is the proper and accurate assessment of the working tool life on which the automatic tool changing/replacement strategy is accomplished [1].

Tool wear rate usually depends on the severity of the employed cutting parameters, especially cutting speed and feed. For given cutting parameters combination, a typical tool life criteria is usually considered as the aggregated time at which an edge wear scar reaches a pre-specified criterion level on one or more locations on the cutting edge: flank, nose, notch or crater [2]. Almost all tool life testing attempts, e.g. [3]-[8] have been carried out considering a one variable-in-turn strategy which usually requires much experimentation to cover a specified cutting domain. Several attempts have been devoted to study the problem when a tool is sequentially employed with variable cutting parameters for different cutting time intervals [1] and [9]-[11]. However, many criticisms of these attempts, regarding the practical feasibility and limitation, have been reported [12]-[14]. Generally, data from tool life testing procedures is used to predict the useful lifetime of a tool edge working under practical conditions similar to those for which the test was conducted. However, if one or more cutting parameters are changed during the working service life of a particular tool, information based on fixed parameters testing is consequently no longer credible. A strategy of compromising between information from two or more fixed-parameter tool life tests may result in misleading and inaccurate outcomes, which adds to the well-known problem of tool life variability and discrepancy [4] and [15]-[17]. Additionally, from the economic viewpoint, it is not wise or practical to replace a tool every time one or more of the operating parameters are changed. Therefore, it is extremely important to have a prior knowledge about tool wear behavior under successive variable cutting conditions. To predict tool life in such situations, it is usually assumed that the further wear of a partly worn edge is independent of previous cutting conditions. The assumptions make possible the assessment of the tool wear increments during consecutive cutting periods and the value is considered as an accumulation of its discrete segments. However, such independence is always assumed without verification and may lead to an enormous inaccuracy.

Additionally, one of the sources of tool wear variability in machining is associated with the way by which the procedures of tool life testing are carried out. The conventional approach is always based on the wear-time relationship which is discretely developed as an accumulation of smaller cut intervals [2]. Testing procedures are usually interrupted for wear measurement and this discrete systematic method is terminated as the high wear rate region is noticed on the aggregated records. Tool life is conventionally determined as the accumulated cutting time corresponding to a prespecified criterion wear level. Through such testing procedures, two influential factors are introduced which affect the proper assessment of tool life. The first, with a likely positive influence, is repeated cooling cycles of the tool substrate every time the cutting is stopped for wear measuring. The second, probably of negative consequence is the repeated shocks every time tool re-engages with the workpiece. These factors affect the wear mechanism of a tool and, therefore, the question now is whether data collected from such a discrete procedure are valid for practical situation where the process is often of an analogous nature.

In this study, two wear variability sources have been theoretically investigated and experimentally verified.

Experimental procedures were designed and carried out to investigate both the effect of changing cutting conditions on tool wear propagation. In addition, further experimental arrangement has been carried out to compare the tool life data from the discrete testing procedures to those from the practical continuous situations. Latter approach aims to clarify the effect of testing continuity on the tool lifetime or, to detect the possible variability in tool life data,

II. Theoretical Analysis

Consider two tools working under two different cutting combinations *S1* and *S2,* Fig. 1. After a working cut time of *t* minutes the two tools exchange their conditions to work under *S2* and *S1* operating combinations respectively. Within the constant wear rate region, the wear slope usually varies to suit the cutting parameters under which the edge operates. In such a situation, there is only one case corresponding to time *Teq* at which both tools attain an equal wear level *Weq* regardless of the effect of the preceding conditions. Around this point, a wear deviation ΔW results depending on the level of the parameters employed and on the cutting duration. Considering *m1* and *m2* are the wear slopes for conditions *S1* and *S2* and, *Wo1* and *Wo2* are the initial wear for both tools, respectively, the wear deviation at the initial stage is:

$$\Delta Wo = Wo2 - Wo1, \tag{1}$$

while its value at the changing time *t* is:

$$\begin{aligned}\Delta W &= W_{S2} - W_{S1} = [Wo2 + m2.t] - [Wo1 + m1.t] \\ &= [Wo2 - Wo1] + t.[m2 - m1] = \Delta Wo + \Delta m.t.\end{aligned} \tag{2}$$

The equilibrium level *Weq* is:

$$\begin{aligned}Weq &= W_{S1} + m2.(Teq - t) = Wo1 + m1.t + m2.(Teq - t) \\ &= W_{S2} + m1.(Teq - t) = Wo2 + m2.t + m1(Teq - t).\end{aligned} \tag{3}$$

Therefore, the equilibrium time *Teq* may be derived as:

$$Teq = \left[\frac{Wo2 - Wo1}{m2 - m1}\right] + 2t = \left[\frac{\Delta Wo}{\Delta m}\right] + 2t. \tag{4}$$

This indicates that the wear deviation depends not only on the previous cut but also on the initial wear which, itself, is cutting condition dependent. Therefore, the assumption of no influence of the preceding conditions on the subsequent tool performance becomes debatable. The equilibrium time *Teq* may be technically interpreted as the time at which an equal wear level *Weq* is developed regardless of the sequence of applying the two different parameters combinations. In other words, for the same tool and, in order to avoid the effect of the preceding cutting parameters, the cut time *t*, at which parameters are changed, should be adjusted so as to consider the initial wear difference ΔWo and, the wear slope difference Δm. Around such an equilibrium point there is always a wear deviation that develops as if the tool continues working under fixed cutting parameters. Deviation distribution depends on the instant at which the switching between parameters occurs. Before reaching *Teq*, wear deviation begins with a maximum value at the instant of the changing time *t* and, gradually decreases until it vanishes at the equilibrium point.

At *ti*, where $t \le ti \le Teq$, wear deviation $\Delta W1$ can be deduced as, Fig. 1:

$$\Delta W1 = \left[\frac{Teq - ti}{Teq - t}\right].\Delta W = \left[\frac{\Delta Wo + \Delta m.(2t - ti)}{\Delta Wo + \Delta m.(2t - t)}\right].(\Delta Wo + \Delta m.t). \tag{5}$$

However, at *tii*, where $Teq \le tii \le 2Teq\text{-}t$, wear deviation is defined as:

$$\Delta W1 = \left[\frac{Teq - ti}{Teq - t}\right].\Delta W = \left[\frac{\Delta Wo + \Delta m.(2t - ti)}{\Delta Wo + \Delta m.(2t - t)}\right].(\Delta Wo + \Delta m.t). \tag{6}$$

As shown by Eqs. 5 and 6, the difference in the wear level, whenever cutting conditions are reversed, depends on the cutting parameters employed and on the instant at which changing occurs along with the difference in the initial wear in both conditions. However, when cutting continues beyond *2Teq-t*, wear deviation at time $tiii > 2Teq\text{-}t$ increases to become:

$$\Delta W3 = \Delta W.\left[\frac{tiii - Teq}{Teq - t}\right] = (\Delta Wo + \Delta m.t).\left[\frac{tiii - Teq}{Teq - t}\right]. \tag{7}$$

Now, let us assume that after tools exchange their operating parameters, Fig. 1, the need arises to retain their original cutting combinations after time *t1,* Fig. 2. While the first tool operating path is *S1-S2-S1*, the path becomes *S2-S1-S2* for the second tool. The question arises: what is the effect of such supposing practical decision?

The resulting wear deviation depends on the instant at which the switching occurs. As shown in Fig. 2, wear deviation at ti where, $t1 \le ti \le 2Teq - t$ result in a minimal value at *t1* and, increases to reach its maximum value at *2Teq - t*. While the minimal deviation $\Delta W1min$ can be defined as $\Delta W1$ in (5), maximum value $\Delta W1max$ can be derived as:

$$\Delta W1max = \Delta W1min + \Delta m(ti - t1). \tag{8}$$

The second possibility is when changing time does not exceed the equilibrium time *Teq* and wear deviation in the interval *ti* to *Teq* is obtained as in $\Delta W2$ defined by (6). Finally, there is a possibility that the changing conditions occurs at *tii* , Fig. 2, where $tii < 2Teq - t$. In such a situation, the wear deviation at any instance tii may be considered as:

$$\Delta W2 = \Delta W3 + \Delta m.[tii - (2Teq - t)]. \tag{9}$$

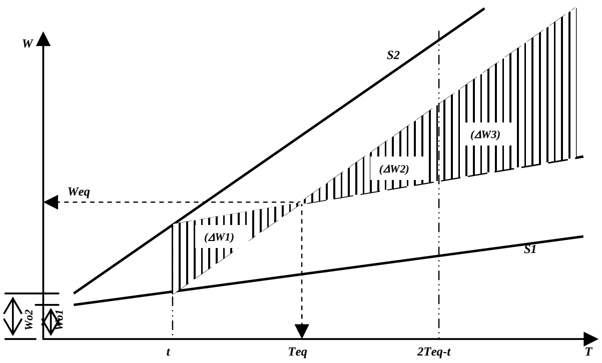

Fig. 1 Wear-Time characteristics at parameters switching

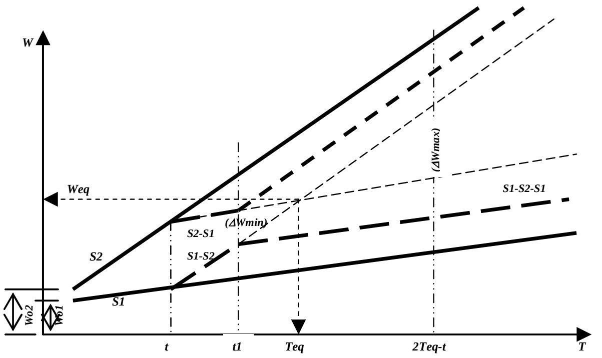

Fig. 2 Two steps two-condition procedures

III. Methods, Results and Discussion

In order to verify the above relationships, experimental procedures were arranged so as to investigate the effect of parameters changing for both multi-coated Sandvik *GC415* and uncoated Kennametal *K21* carbide inserts when they are used to turn cut a hardened and tempered alloy steel *En19*. As recommended by the tool manufacturers, dry cutting was carried out since, in many applications, using cutting fluids causes frequent heat and cooling cycles that, in turn, lead to microcracks of the tool substrate. To suit the capacity of the employed Colchester centre-lathe, workpiece billets were prepared with effective length of 500 mm and net diameter of 150 mm. Among various tool wear modes, nose wear was considered in the study since, from experience (Oraby *et al.* 2004), it was found to be the most influential on wear mode either on the cutting edge or on the machined surface. Edge wear is evaluated using a high-precision SIP three-axis universal measuring optical microscope with a special insert seating arrangement.

A. Fixed-Parameters Testing (Conventional Wear-Time Testing)

For comparison purposes, it was necessary to generate machinability data using the conventional standard procedures [2] and [18]. Eight independent experiments (T1 to T8) were carried out as described in Table I. While the effect of the cutting speed was considered for coated inserts (Set 1) and for uncoated inserts (Set2) the effect of feed was dealt with in Sets 3 and 4. Due to its limited influence [19], depth of cut was kept constant in each group.

For all experiments, results indicated a conventional wear-time trend where a constant wear region was developed that was followed by a high wear rate stage (plastic deformation zone). The duration of the constant wear region was determined by the level of cutting parameters such that more severe parameters led to higher wear rate and accordingly, shorter tool life.

Relations (3) and (4) were used to extract the numerical values of each equilibrium point (Teq) and its corresponding wear level (Weq). To get the difference in the initial wear (ΔWo) and in the wear (Δm), a first-order polynomial representing the experimental data for each test is proposed as:

$$W = \beta + m.t. \tag{10}$$

This relation merely represents the constant wear region part of the trend and, therefore, data within the high wear region was excluded from analysis. However, the constant part of the polynomial (ß) represents the value of the initial wear (Wo) and, was computed as the intercept of the vertical axis at zero time using the first few points, preferably two. Results of such an analysis are listed in Table II for each set; the two machining combinations are mutually changed. However, it is noticed that the use of feeds, T5 and T7, usually leads to a discontinuous unstable chipping mechanism leading to greater level of initial wear. This justifies the negative initial wear difference for Sets 3 and 4 (see Table II). However, as the edge passed its initial wear region, the general trend of higher wear rate for greater feedrate settled down. Values of *Weq* and *Weq* at different changing time *t* were extracted from (3) and (4) as listed in Table III.

B. Variable-Parameters Testing

Machinability data, usually provided by the tool manufacturer, is usually based on fixed-parameters testing procedures. To examine the possibility, claimed in the current work, to adapt such information to suit variable-parameter applications, a further testing arrangement was suggested as indicated in Table IV. For each set, the companion two parent tests were carried out with specific parameters for a certain cutting time, after which they interchanged parameters. The resulting values of *Teq* and *Weq* were experimentally determined and then, compared to those obtained from the fixed-parameters testing shown in Tables II and III.

As listed in Table IV, testing was carried out individually for each set changing time *t* values of *4, 6,* and *8* min leading to three separate subsets. For instance, Set1(4) implies that both tools in Set1 are used and they exchange conditions after cut time of *t = 4* min. Also, *T(i-j-k)* where *i=1,3,5* or *7*, *j = 4, 6*, or *8* min. and, *k = 2, 4,6* or *8*, means that both tools *Ti* and *Tk* (Table I), were used as parent tests with a changing time *t = j*. For instance, T(1-6-2) means that T1 and T2 are used and, they exchange conditions at a cut time of *6* min. For all experiments, the general trend was that there is an equilibrium wear-point at which wear deviation vanishes as evaluated earlier. Figs. 3 and 4 summarize a comparison between experimental and theoretical values of the equivalent time *Teq* and wear *Weq* as derived by (3) and (4). For most subsets, an excellent agreement was obtained with less accuracy for subsets Set2(6) and Set3(4) when a *Teq* is compared, Fig. 4. With an average error for all subsets of 1.85 min time and 0.0119 mm wear for *Teq* and *Weq*, the proposed approach to predict both of *Teq* and *Weq* from fixed-parameter testing is reliable.

TABLE I
FIXED-PARAMETERS TESTING ARRANGEMENT

Test No.	Cutting Conditions			Edge Conditions
	Speed (m/min)	Feed (mm/rev)	Depth (mm)	
Set 1:				
T1	70	0.12	2.00	Coated
T2	140	0.12	2.00	Coated
Set2:				
T3	70	0.12	2.00	Uncoated
T4	140	0.12	2.00	Uncoated
Set 3:				
T5	203	0.06	1.5	Coated
T6	203	0.2	1.5	Coated
Set 4:				
T7	203	0.06	1.5	Uncoated
T8	203	0.2	1.5	Uncoated

For each set, data from fixed-parameter testing were superimposed on the corresponding values from the variable-parameter testing as shown in Figs. 5a-14a. For each subset, experimental wear deviation *ΔW* values around the equilibrium point were extracted, plotted and compared to their counterpart derived from (5) and (6). As shown in Figs. 5b-14b, wear deviation is plotted along the time axis as positive and negative values around the equilibrium point.

For each set, data from fixed-parameter testing were superimposed on the corresponding values from the variable-parameter testing as shown in Figs. 5a-14a. For each subset, experimental wear deviation *ΔW* values around the equilibrium point were extracted, plotted and compared to their counterpart derived from (5) and (6). As shown in Figs. 5b-14b, wear deviation is plotted along the time axis as positive and negative values around the equilibrium point.

TABLE II
EVALUATED INITIAL WEAR AND WEAR RATE OF FIXED-PARAMETERS TESTING

Set No.	Wo1 (mm.)	Wo2 (mm)	ΔWo (mm)	m1	m2	Δm
Set1:(T1&T2)	0.118	0.141	0.023	0.0039	0.00558	0.00168
Set2:(T3&T4)	0.12	0.139	0.019	0.00665	0.00683	0.00018
Set3:(T5&T6)	0.166	0.127	-0.039	0.00229	0.01147	0.00918
Set4:(T7&T8)	0.160	0.09	-0.07	0.022	0.05	0.028

TABLE III
EQUILIBRIUM TIME AND EQUIVALENT WEAR OF FIXED-PARAMETERS TESTING

Set Sequence	t= 4 min.		t= 6 min.		t= 8 min.	
	Teq (min)	Weq (mm)	Teq (min)	Weq (mm)	Teq (min)	Weq (mm)
Set1	21.7	0.232	25.7	0.251	29.7	0.27
Set2	8.2	0.193	12.2	0.221	16.2	0.248
Set3	3.7	0.171	7.7	0.199	11.7	0.277
Set4	5.5	0.323	9.5	0.467	13.5	0.611

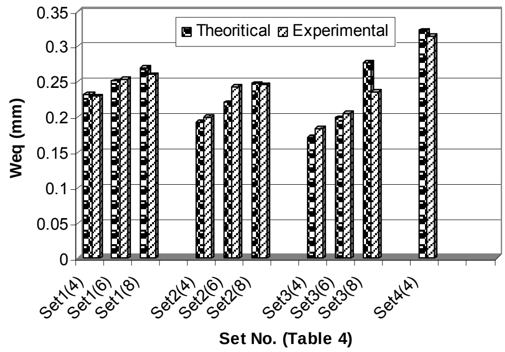

Fig. 3 Comparison between theoretical and experimental equivalent wear

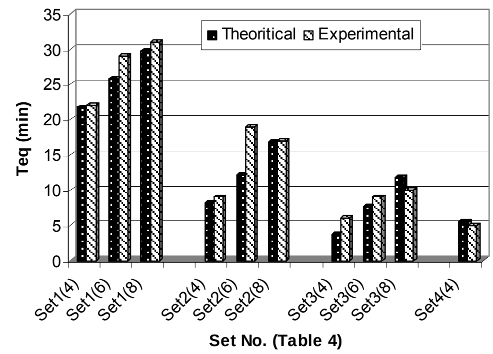

Fig. 4 Comparison between theoretical and experimental equivalent time

Regarding the comparison between the results from fixed and variable parameters, it is found that the values of wear deviation *ΔW* were much closer and more consistently distributed for uncoated tips, which is due to the different mechanism by which coated tools deform, especially at the constant wear rate zone. However, when the uncoated tool was used in conjunction with high speed or feed, the equilibrium point approached the plastic deformation zone, Figs. 10-13, and this degrades the reliability of wear deviation values after the equilibrium point.

In addition, a better correlation was noticed between the values and distribution of the wear deviation before the equilibrium point and this is due to the fact that the tool stayed in service longer than the time between the changing and the equilibrium point. Also, it is possible that the tool entered or, at least, approached the plastic deformation zone.

Generally, it can be concluded that there is a good correlation between information derived from fixed- and variable-parameter testing procedures regarding *Weq*, *Teq* or *ΔW*. Therefore, it is possible to use the proposed approach of extracting information about a practical machining with variable conditions without the need to conduct variable conditions testing. For modern machining technology such as adaptive control, where the tool is always subjected to changing conditions, the proposed strategy may be fitted within suitable software to be included in the optimization algorithm of the system.

TABLE IV
ARRANGEMENT FOR VARIABLE-PARAMETER TESTING

Set No.	Tests Symbol	Conditions
Set1:		
Set1(4)	T(1-4-2)vs T(2-4-1)	Speed= 70 vs 140 m/min.
Set1(6)	T(1-6-2)vs T(2-6-1)	Feed 0.12 mm/rev.
Set1(8)	T(1-8-2)vs T(2-8-1)	Depth = 2.00 mm. Coated
Set2:		
Set2(4)	T(3-4-4)vs T(4-4-3)	Speed= 70 vs 140 m/min.
Set2(6)	T(3-6-4)vs T(4-6-3)	Feed = 0.12 mm/rev.
Set2(8)	T(3-8-4)vs T(4-8-3)	Depth = 2.00 mm.Uncoated
Set3:		
Set3(4)	T(5-4-6)vs T(6-4-5)	Speed= 203 m/min.
Set3(6)	T(5-6-6)vs T(6-6-5)	Feed = 0.06 vs 0.2 mm/rev.
Set3(8)	T(5-8-6)vs T(6-8-5)	Depth = 1.5 mm. Coated
Set4:		
Set4(4)	T(7-4-8) vs T(8-4-7)	Speed= 203 m/min. Feed = 0.06 vs 0.2 mm/rev. Depth = 1.5 mm.Uncoated

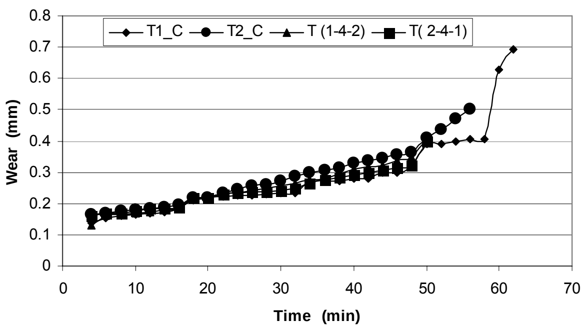

Fig. 5a: Wear-time curves for set1(4)

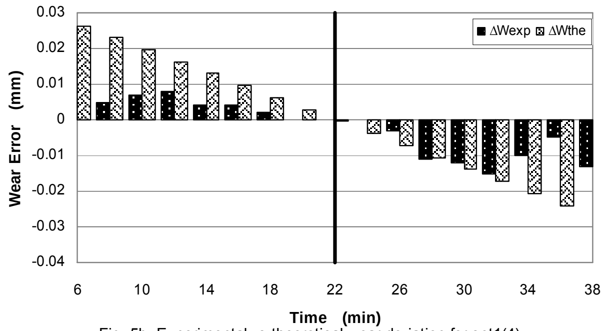

Fig. 5b: Experimental vs theoretical wear deviation for set1(4)

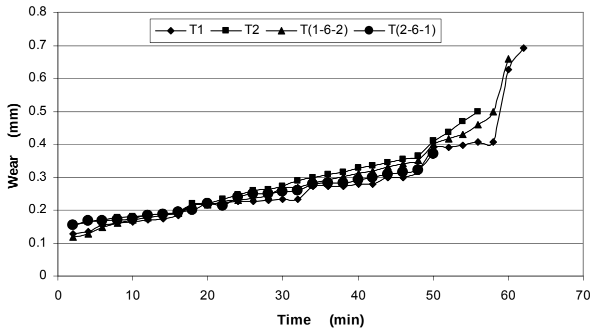

Fig. 6a: Wear-time curves for set1(6)

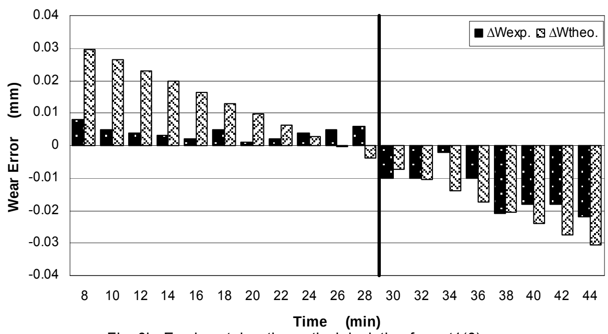

Fig. 6b: Exprimental vs theoretical deviation for set1(6)

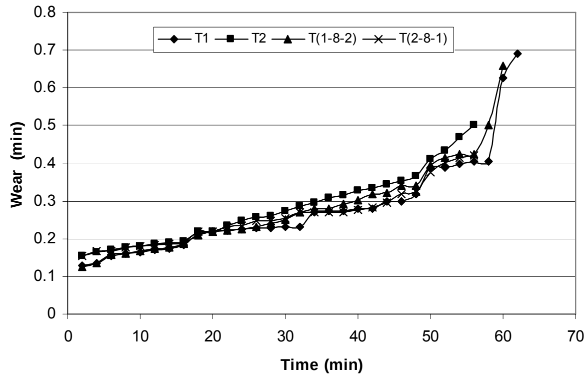

Fig. 7a: Wear-time curves for set1(8)

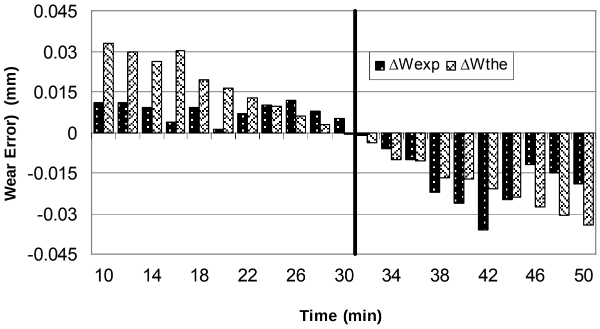

Fig. 7b: Experimental vs theoretical deviation for set1(8)

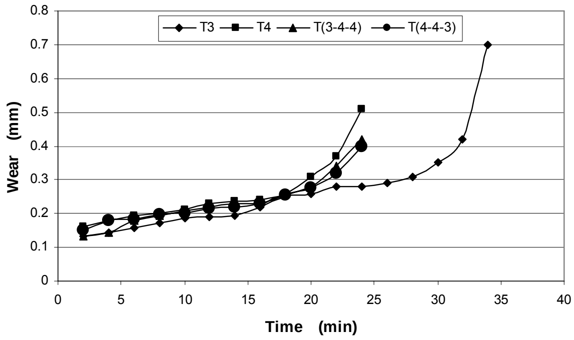

Fig. 8a: Wear-time curves for set2(4)

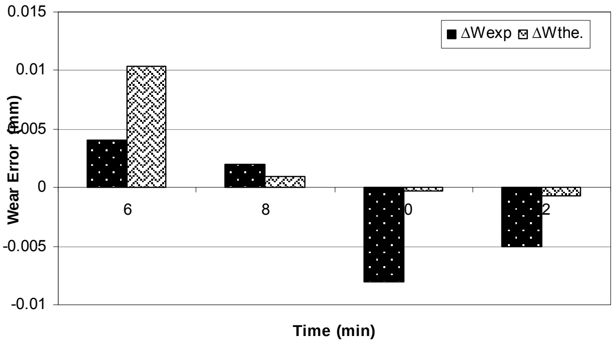

Fig. 8b: Experimental vs theoretical wear deviation for set2(4)

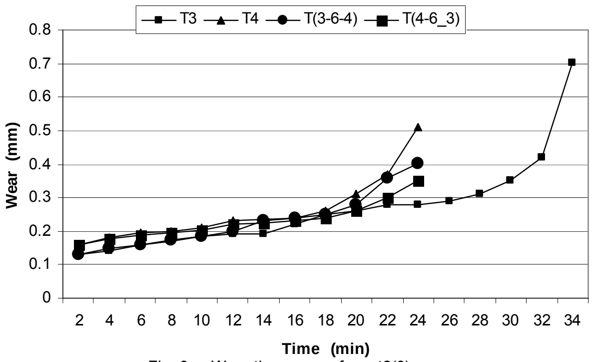

Fig. 9a: Wear-time curves for set2(6)

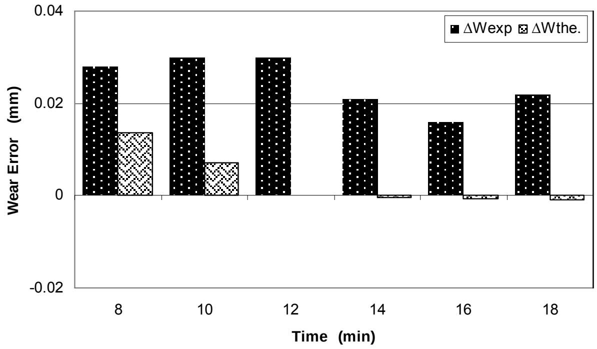

Fig. 9b: Experimental vs theoretical deviation for set2(6)

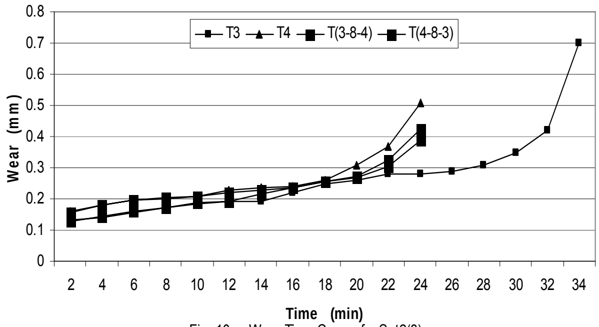

Fig. 10a: Wear-Time Curves for Set2(8)

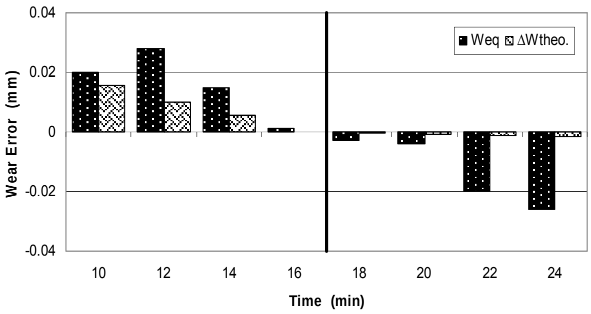

Fig. 10b: Experimental vs theoretical deviation for set2(8)

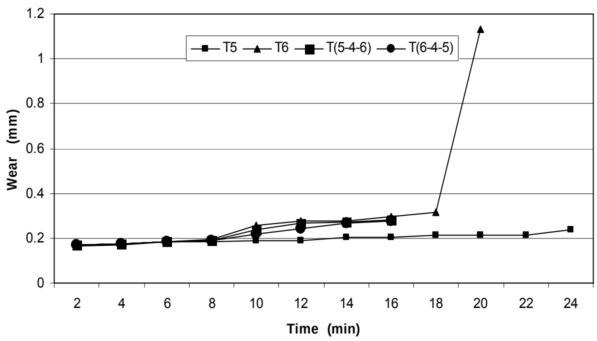

Fig. 11a: Wear-time curves for set3(4)

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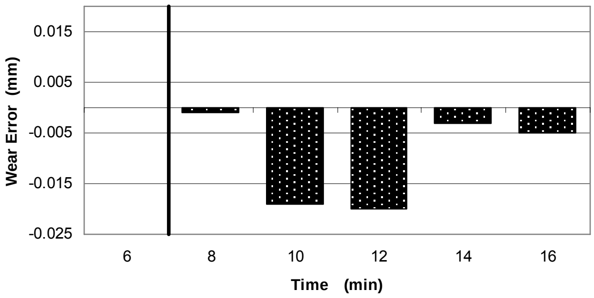

Fig. 11b: Experimental wear deviation for set3(4)

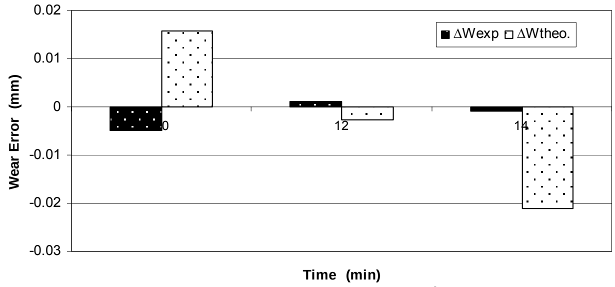

Fig. 13b: Experimental and theoretical deviation for set3(8)

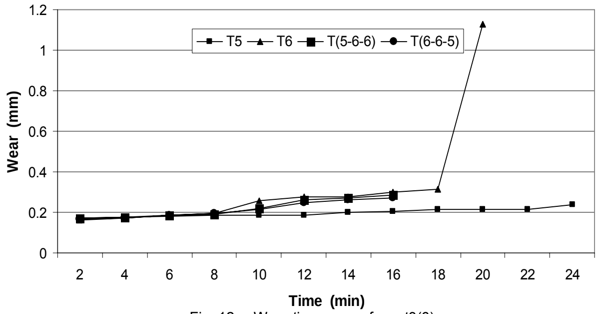

Fig. 12a: Wear-time curves for set3(6)

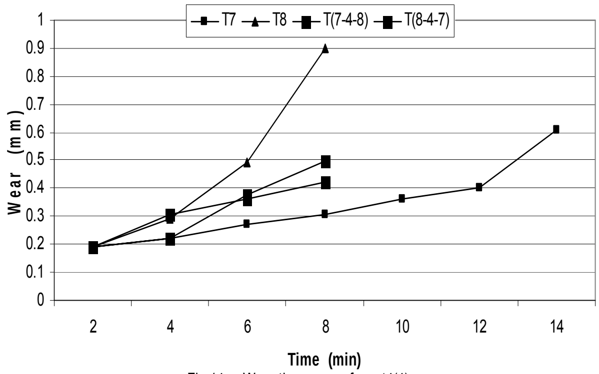

Fig.14a: Wear-time curves for set4(4)

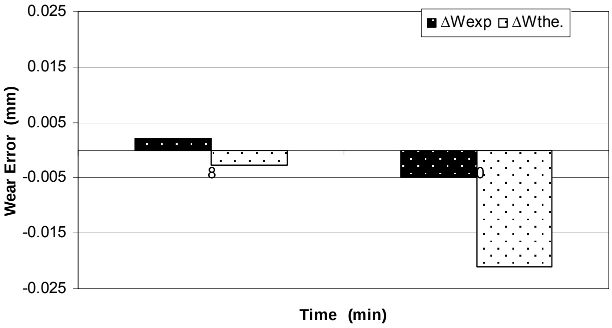

Fig. 12b: Experimental and theoretical deviation for set3(6)

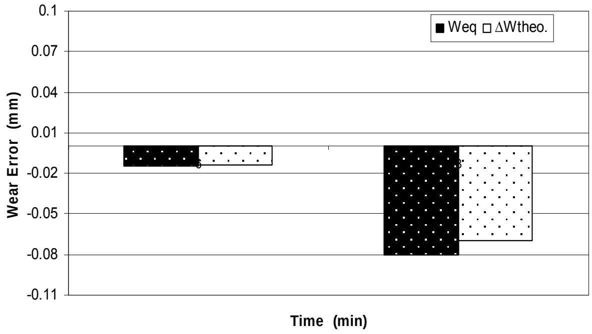

Fig. 14b: Experimental and theoretical wear deviation for set4(4)

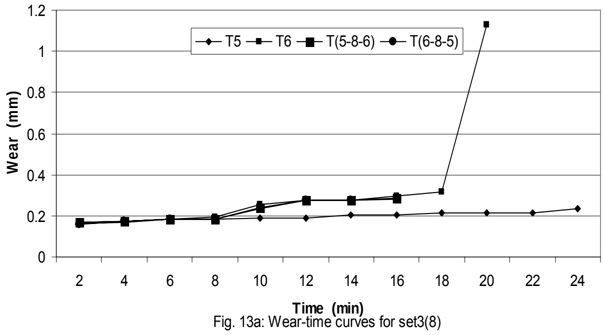

Fig. 13a: Wear-time curves for set3(8)

IV. Credibility of Conventional Tool Life Testing

In order to investigate the existing tool life variability due to discrete nature of practical machining, a series of experiments were developed in which the discrete and the continuous techniques were compared. The eight experiments listed in Table I were repeated leaving the tool in service as long as possible without interruption. However, and due to the limitation imposed by the specimen length and the employed feed, the tool was taken away for wear measurement either when the whole length was consumed or when the tool catastrophically or abruptly failed.

The results in Fig. 15(a-g) indicate that a tool life is relatively longer for the discrete testing procedures. However, for coated tools, Figs. 15a,b,e,f, the difference between wear values from discrete and continuous testing was not as great as

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for uncoated tools, Figs. 15c,d,g,h. Also, wear difference was less as each of speed and feed was reduced.

These observations may be attributed to the positive effect of the testing procedure parameters and the way the test was conducted [8]. Natural cooling between subtests may overcome the negative effect of the multiple entrance shocks of discrete testing. In continuous cutting, the temperature is gradually maintained inside the tool substrate leading to the escalation of wear and, consequently, the early activation of the edge's plastic deformation. In addition, interruption intervals usually allow for the solidification of strain-hardened welded joints in the cutting vicinity. This solid material is stuck into the grooves developed on the cutting edge to add an additional protection against further edge wear development. This may be further compressed when process is resumed. At some stages, the build up material portion is broken down and a new filling begins to develop leading to less material removed by the cutting edge. This mechanism of material frequent forming and removal could be the reason behind force fluctuation usually noticed when machining especially at low and moderate speed and/or feed [19].

The use of tool in a discrete machining process using fixed-parameters machinability data can lead to disastrous consequences when a tool is left in service too long. Although there is not enough information available to set a safety factor since the deviation is condition-dependent, a roughly difference to be accounted for may be proposed as from 10 to 40% and, from 30 to 50% for coated and uncoated tools, respectively (see the individual plots).

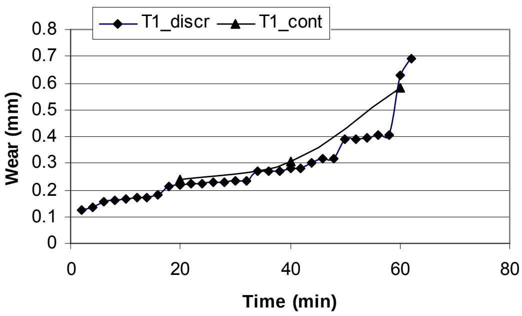

Fig. 15a: Continuous vs discrete toollLife testing for T1

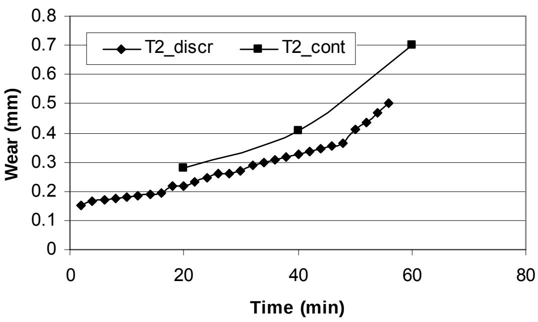

Fig. 15b: Continuous vs discrete tool life testing for T2

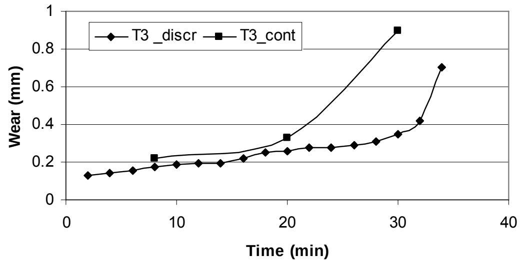

Fig. 15c: Continuous vs discrete tool life testing for T3

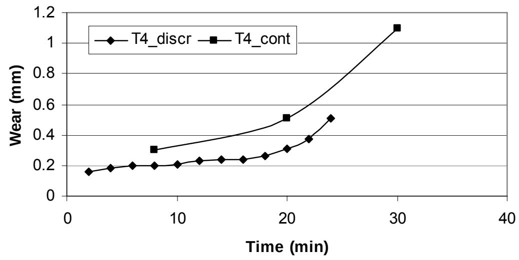

Fig. 15d: Continuous vs discrete tool life testing for T4

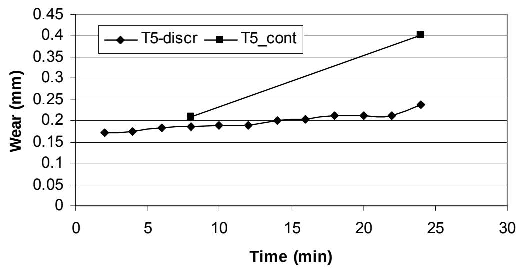

Fig. 15e: Continuous vs discrete tool life testing for T5

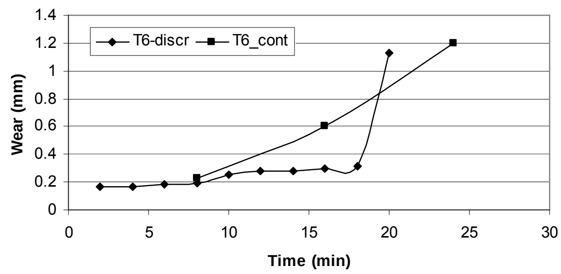

Fig. 15f: Continuous vs discrete tool life testing for T6

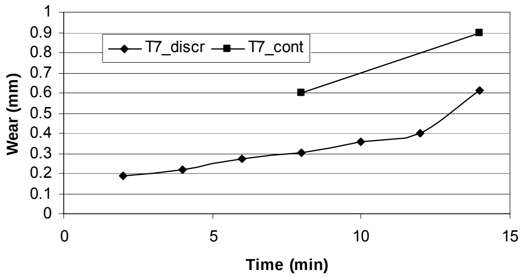

Fig. 15g: Continuous vs discrete tool life testing for T7

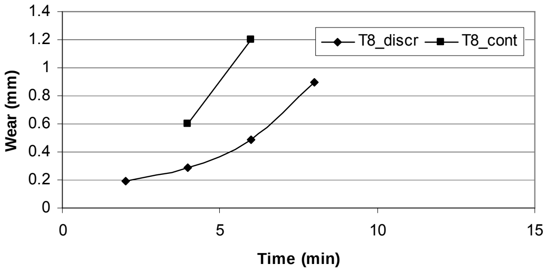

Fig. 15h: Continuous vs discrete tool life testing for T8

V. Conclusion

The current study illustrates how information from fixed-parameter testing can be exploited to yield an acceptable approach to be applied for practical variable-parameter machining. Experimental verification supported the proposed technique and showed that, it is possible to plan for variable-parameter cutting without the need for elaborate testing procedures. It is easier to interpret the proposed technique in modern manufacturing systems by fitting its mathematical forms into suitable software to be included in the host computer of the system.

Another source of wear variability emerges when information from the conventional discrete tool life testing procedures are used to estimate the life of a tool edge working under practical continuous cutting. Results have indicated that cutting interruption to measure wear or, for any other reason, benefits the operation in terms of less wear level or longer tool lifetime. At a given cut time, the difference in the developed wear level for discrete and continuous processes is dependent on the type of tool and on the level of operating conditions. Less difference is noticed for coated inserts and this difference is increased as speed and/or feed increases. These results should be taken in consideration if accurate and safe tool life estimation strategy is to be relied upon in practical applications.

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